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A PRELIMINARY MECHANICAL DESIGN EVALUATION OF THE WIKISPEED CAR: FOR LIGHT-WEIGHTING IMPLICATIONS

ABSTRACT

Purpose: Road passenger transportation faces a global challenge of reducing environmental pollution and greenhouse gas emissions due to vehicle weight increases needed to enhance passenger safety and comfort. This paper presents a preliminary mechanical design evaluation of the Wikispeed Car (with a focus on body bending, body torsion and body crash) to assess light-weighting implications and improve the vehicle's environmental performance without compromising safety.

Approach: For this research, finite element analysis (FEA) were performed to examine the Wikispeed chassis for light-weighting opportunities in three key aspects of the vehicle's design, namely: i) for body bending the rockers (or longitudinal tubes); ii) for body torsion (again on the rockers but also the chassis as a whole); and iii) for crash safety – on the frontal crash structure. A two phase approach was adopted, namely: in phase one, a 3D CAD geometry was generated; and in phase two FEA was generated. The combination of analysis results was used to develop the virtual model using FEA tools and the model was updated based on the correlation process.

Findings: The research revealed that changing the specified material Aluminium Alloy 6061-T651 to Magnesium EN-MB10020 allows vehicle mass to be reduced by an estimated 110kg, thus, producing a concomitant 10% improvement in fuel economy. The initial results imply that the current beam design made from magnesium would perform worst during a crash as the force required to buckle the beam is the lowest (between 95.2 kN and 134 kN). Steel has the largest bandwidth of force required for buckling and also requires the largest force for buckling (between 317 kN and 540 kN).

Originality: This is the first study of its kind to compare and contrast between material substitution and its impact upon Wikispeed car safety and performance.

KEYWORDS

Finite element analysis, light-weight materials, emission reduction, greenhouse gas emissions, Wikispeed Car.

INTRODUCTION

Tougher regulatory requirements intended to control greenhouse gas emissions from vehicles have prompted manufacturers to be technologically innovative in both the design and manufacture of their cars. Of the various options available, vehicle weight reduction remains a prominent and viable option (Harvey, 2018). Specifically, the use of lightweight materials to replace conventional steel in passenger vehicles with internal combustion engines (ICE) has gained noteworthy attention (Luk *et al.,* 2017). This is because lightweight materials substitution can help to reduce fuel consumption and the formation of exhaust emissions (AlSabbagh *et al.,* 2017; Fernández, 2018; Luján *et al.,* 2018). Of the various design options available, the greatest opportunity to reduce vehicle weight comes from the body structure whilst further weight reductions can be achieved by downsizing other compartments such as the engine; where a compartment represents a major section of a vehicle (e.g. engine, transmission, body structure) that contains numerous components (Shi *et al.,* 2007).

A widely acclaimed design innovation is the Wikispeed car that was developed as an open-source project founded in 2006 by Joe Justice (Kostakis *et al.*, 2015). The project sought to create an ultra-lightweight, ultra-fuel-efficient and affordable 'roadster car' that is fun, fast and pleasurable to drive. The Wikispeed car evolved from an eco-challenge racing car which has meant that luxury has been forsaken for a lightweight sports car without a roof, lockable trunk and doors (Socha *et al.,* 2013). The Wikispeed can accelerate from 0 to 60 miles per hour (mph) in less than 5 seconds, has a top speed of 140 mph, weighs 1,404 imperial pounds and is capable of 100 miles per gallon (mpg).

Against this contextual backdrop of progressive engineering design to solve real-world problems, this paper investigates the structural and safety performance of the Wikispeed car in terms of bending stiffness, torsional stiffness, and crashworthiness (through analytical calculations). The structural elements of the Wikispeed car are critically analysed using ANSYS FEA software and the results and findings of light-weight substitution opportunities are discussed. The research concludes with design recommendations that could enhance the environmental performance of the car without unduly compromising passenger safety.

LIGHTWEIGHT MATERIALS AND THEIR APPLICATIONS

Sustainable design in the early phases of new passenger vehicle development has gained paramount importance within both society and the automotive industry business over recent decades (Grey and Tarascon, 2017). Innovative concepts such as the use of lightweight material design and crashworthiness have consequently gained prominent attention for their high strength, stiffness and high energy absorption capabilities (Pradeep *et al.,* 2017). In the initial product development phases, designers and engineers must consider material selection to accurately establish lightweight and durability parameters (Danilecki *et al.,* 2017). Another concomitant objective being to present a structural analysis of lightweight components selected – to enhance mass reduction, reduce greenhouse gas emissions and in so doing, decrease energy consumption (Xiong *et al.,* 2018).

Both the extant literature and manufacturer literature are replete with examples of vehicle light-weighting studies and the benefits of these. Traditionally, low density materials such as aluminium, steel, magnesium and composite materials have been prominently used in the automobile industry to replace ferrous alloys (Barton and Fieldhouse, 2018). Higher strength, ductility is provided by ferrous alloys at a lower cost when compared to low density alloys (Melado *et al.,* 2017). High strength to weight ratio is provided by ultra-high strength cast alloys – such materials properties produce structural components for passenger car vehicles (especially for the production of thinner wall section thus decreasing the overall weight of the component) (Mohrbacher, 2013). For example, Figure 1 illustrates that increasing the yield strength of steel from 200MPa to 550MPa a typical structural component weight is reduced by approximately 62.5% under different load cases.

<Insert Figure 1 about here>

However, from a historical perspective and without changing the interior volumes of passenger cars, the average vehicle weight increased by approximately 118kg between 1995 to 2010, and since 2010 vehicle weight has remained constant (Joost and Krajewski, 2017). More recently, aluminium sheet was used to manufacture the 2015 Ford 150 body structure and closure panels, whereas the Cadilac ATS and CT6 used high strength steel and aluminium extrusions (Tang, 2017). From 2006 to 2013, the Chevrolet Corvette Z06 cradle was made out magnesium, albeit it also showcased an aluminium hydro formed structure which was a variant to Corvette base which was made out of steel (Taub and Luo, 2015). A key material substitution of magnesium to aluminium enabled: weight reduction at the front of the vehicle; galvanic corrosion reduction; and achieved the same stiffness. Another application of lightweight materials (i.e. magnesium) was for instrument panels or cross bar beams that were traditionally made out of steel stampings prior to 2000's (Taub *et al.*, 2007). General Motors, also generated high volumes of magnesium made instrument panels for their cars during the period 2005 to 2006 (Hong and Shin, 2017). Post 2010 and the global economic crisis, the usage of magnesium instruments drastically fell due to rising pricing, which resulted in the development of tubular steel designs to reduce overall vehicle weight (Sasanka and Kumar, 2017). In 2012, the Cadillac STS manufactured an aluminium deck lid (and magnesium inner parts with outer coating of aluminium) using General Motor's quick plastic forming (QPF) technology (Luo *et al.,* 2016). This design innovation increased mass savings of 1.5kg for the deck lid as compared to previous versions (Muthuraj *et al.,* 2017). While conducting a life cycle assessment, Koltun *et al.,* (2016) performed a sensitivity analysis and demonstrated that significant mass reduction of components can be readily achieved by using Australian magnesium vis-a-vis standard US aluminium. To illustrate light-weighting effects, Ding *et al*. (2016) conducted a sensitivity analysis study to show different energy savings on automobile parts in China by replacing them with aluminium. Results recorded over a vehicle life cycle of 200,000 km driving revealed that when typical steel parts were replaced with aluminium parts, the vehicle consumed 1,447 to 1,590 litres less gasoline. A tailored model to assess the environmental benefits of light-weighting on diesel turbocharged vehicles was presented by Delogu *et al.,* (2016) and was based upon fuel reduction value (FRV). Their results (*ibid*) showed that the FRV was within the range of 0.115–0.143 and 0.142–0.388 L/100 km × 100 kg for mass reduction only and powertrain adaptation purposes. Del Pero *et al.,* (2017) performed a life-cycle assessment of 2015 European market vehicle case studies to formulate a new method to estimate fuel consumption reduction by means of FRV. The authors (*ibid*) concluded that the method should be extended to the mass induced energy consumption modelling to electric and hybrid vehicles. Koulton *et al.,* (2016) performed a sensitivity analysis of a convertor housing using magnesium in the die-casting, trimming and finishing processes; their study (*ibid*) demonstrated that a reduction in total greenhouse gas emissions could be readily achieved. Kiani *et al*. (2014) conducted a structural optimization on the 1996 Dodge Neon car model, to develop a lightweight car design. The authors (*ibid*) replaced 22 steel parts with magnesium AZ31 and the design optimization resulted in saving 46.7 kg of overall weight and an approximate mass reduction of 44.3% when compared to the initial steel design.

Other applications include the usage of composite materials such as kenaf/glass fibre and glass mat thermoplastic – these materials introduce a massive challenge to designers and automotive engineering in optimisation of passenger vehicle design due to a large count of design variables (e.g. vehicle weight and driving conditions). An FEA investigation was carried out by Hosseinzadeh *et al.,* (2005) on the bumper beam system manufactured from glass thermoplastic to consider the low-velocity impact performance. Davoodi *et al.,* (2010) conducted their FEA investigation on the selection of the best geometric parameters to improve the performance of the car bumper system manufactured from kenaf/glass fibre and illustrated that vehicle performance improved via overall weight reduction. Bellingardi *et al.,* (2013) employed major design parameters such as peak load and energy absorption to develop an optimisation evaluation criteria of an open integrated crash box and bumper beam system – thus improving crashworthiness. Yet, despite this extensive research conducted, ample opportunities remain to conduct additional studies into vehicle light-weighting and its impact upon car performance, environmental impact and safety design.

METHODOLOGICAL EVALUATION OF STRESSES

In this case study, finite element analysis (FEA) is performed to examine the Wikispeed chassis for light-weighting opportunities in three key aspects of the vehicle's design, namely: i) for body bending the rockers (or longitudinal tubes); ii) for body torsion (again the rockers but also the chassis as a whole); and iii) for crash safety - on the front crash structure (through the presentation of analytical calculations). The methodological framework adopted in this paper is defined and delineated in Figure 2 and consisted of into two phases. In phase one, a 3D CAD geometry is generated and this is followed by FEA in phase two. The combination of analysis results was used to develop the virtual model using FEA tools and the model was updated based on the correlation process.

<Insert Figure 2 about here>

Specifically, Malen's approach to conducting FE calculations for the vehicle's components is outlined for the calculations (c.f. Malen, 2011). For the body in bending analysis, a single lower longitudinal chassis beam, referred as the side rocker beam has been considered; where σ_{CR} and M_{CR} denote the critical stress and critical bending moment respectively. The bending stiffness of the entire chassis is calculated using body bending stiffness; where k is a function of the total length of the beam; L is the length between the supports; l is the rigidly fixed masses on the chassis M; and the desired bending frequency (f_n) can be calculated using following equations:

$$\sigma_{CR} = \frac{k\pi^2 E}{12(1-\mu^2)(\frac{b}{t})^2} \quad \text{Eq. 1}$$

$$\sigma_{CR} = \frac{M_{CR}y}{I} \quad \text{Eq. 2}$$

$$k = 0.09566\ (\frac{l}{L})^3\ M(2\pi f_n)^2 \quad \text{Eq. 3}$$

For the body torsion analysis, first the side rocker beam was analysed. The angle of rotation (θ) and the shear stress in each of the walls of the beam (τ) resulting from a torsional force of 500 Nm were calculated. Secondly, the torsional stiffness of the chassis structure (K) has been calculated by simplifying the chassis structure into a box of open sides. Finally, the strain in the joint ($eJOI$) was calculated together with the strain in each of the beams in question ($eBEAM$). The effective torsional constant ($Jeff$) was calculated solely to enable the angle of rotation (θ).

$$J_{eff} = \frac{4A^2 t}{S} \quad \text{Eq. 4}$$

$$\emptyset = \frac{TL}{GJ_{eff}} \quad \text{Eq. 5}$$

$$\tau = \frac{T}{2At} \quad \text{Eq. 6}$$

Initially the effective shear rigidity ((Gt)) and torsional stiffness of each side of the box (Ks) were calculated. This allows the torsional stiffness of the entire structure to be calculated.

$$(Gt)_{eff} = \frac{Fb}{\delta a} \quad \text{Eq. 7}$$

$$K_s = \frac{4k_j}{L^2} \quad \text{Eq. 8}$$

$$K = 4h^2w^2 \left\{ \frac{1}{\left(\frac{1}{K_{Front}} + \frac{1}{K_{Rear}} + \frac{1}{K_{L.Side}} + \frac{1}{K_{R.Side}} + \frac{1}{K_{Bottom}} + \frac{1}{K_{Top}} \right)} \right\} \quad \text{Eq. 9}$$

Joint efficiency, beam strain and joint strain for the hinge pillar and rocker pillar were used to calculate joint efficiency; the strain in the two beams and the strain in the joint respectively were calculated using the following equations:

$$e_{beam} = \frac{L}{6EI}(3M^2) \qquad \text{Eq. 10}$$

$$e_{joint} = \frac{M^2}{2k_j} \qquad \text{Eq. 11}$$

For crash safety calculations undertaken, the axial compressive load sought to find which side rocker beam would buckle (P_U). For the second stage of crashworthiness calculations, the crush efficiency (η) has been calculated ensuring the result satisfies results from the Wikispeed crash test in order to find the maximum deceleration of the cabin (a_{max}). From which, using vehicle and material data, the maximum force (F_{max}) the average force (F_{avg}) and the average crush force per side rocker beam were calculated.

$$w_1 = 0.894b\sqrt{\frac{\sigma_{CR}}{\sigma_s}} \qquad \text{Eq. 12}$$

$$w_2 = b\sqrt{\frac{\sigma_{CR}}{\sigma_s}}\ (1 - 0.22\sqrt{\frac{\sigma_{CR}}{\sigma_s}}) \qquad \text{Eq. 13}$$

$$P_U = \sigma_s(4wt) \qquad \text{Eq. 14}$$

$$\eta = \frac{V_o^2}{2\Delta a_{max}} \qquad \text{Eq. 15}$$

$$F_{max} = ma_{max} \qquad \text{Eq. 16}$$

$$F_{avg} = 386t^{1.86}b^{0.14}\sigma_s{}^{0.57} \qquad \text{Eq. 17}$$

FINITE ELEMENT ANALYSIS OF THE WIKISPEED CAR

The analysis of body in bending, torsion and crash worthiness enabled potential light-weighting opportunities to be explored. To allow a comparative evaluation of material performance to be completed, calculations for three different materials; structural steel BS EN 10025-3:2004, aluminium alloy 6061-T651 and magnesium EN-MB10020 were completed (refer to Table 1 for material properties; such indicates a weight saving for

Aluminium of 0.65%, and for Magnesium of 0.78%) (Brockenbrough and Merritt, 1999; Mondolfo, 2013; Mordike and Ebert, 2001).

<Table 1 about here>

Body in Bending

FEA was carried out on one of the four identical rocker beams going through the car and revealed that the maximum bending moment that aluminium rockers can endure is 8.27kNm per rocker before they fail. Figure 3 is a representation of the rocker made from steel with an applied moment of 23.66kNm to one end. The stress on the top side of the rocker is around 627 MPa much like the critical stress found from the calculations which was 626MPa. The same calculations illustrated that by using steel, the strength of the beam will increase by 286% and would be around 33.5% cheaper; albeit a 289% increase in weight is needed. The total bending moment diagram of the rocker beam is shown in Figure 4.

<Insert Figures 3 and 4 about here>

From the structural analysis of one of the four identical rocker beams, it was found that for aluminium rockers, the maximum bending moment they can endure is 8.27 kNm per rocker before it fails. The same calculations for steel revealed that this material will increase the strength of the beam (refer to Table 2). Magnesium (as a viable alternative choice of material) is the lightest of the three materials at only 64.1% of the weight of aluminium and 22.2% of steel. The reduced weight comes at a design-cost because it is 37.4% weaker than aluminium and 78.1% weaker than steel; although the purchase price is roughly the same as aluminium. Figure 5 illustrates that the same beam made from magnesium could sustain a bending moment of 964 Nm, or a mass of approximately 490 kg at its centre. This gives a more reasonable factor of safety of 0.314, thus making magnesium a suitable material for selection for the side rocker beam while considering design for bending (refer to Figure 6).

<Insert Table 2 and Figures 5 and 6 about here>

Body in Torsion

For analysis of the Wikispeed car in torsion, the calculations performed are based entirely from the CAD data available at the time of this study, which excluded dimensions of the floor panel. Therefore, in the simplification of the chassis structure and for the approximation of its torsional stiffness, the chassis has been considered to be a cuboid, made of tubes and with open sides. Table 3 reveals that for the torsion calculations, the magnesium beam has the worst torsional performance properties of the three materials tested under these conditions.

<Insert Table 3 about here>

Magnesium having a resultant angle of rotation almost five times that of steel which has the smallest resultant angle of rotation. This initial finding suggests that from a design for torsion stance, steel is the most suitable material – whilst such is true (and steel is by far the cheapest material), it also has the highest density. This weight implication would negatively impact fuel economy. Figure 7 illustrates the total deformation on the side frame.

<Insert Figure 7 about here>

The second set of calculations show the torsional stiffness of the entire vehicle to be 3,660 Nm/deg. This is a conservative estimate as the assumptions made in these calculations are not strictly true of the actual design. For example, the torsional stiffness added to the vehicle by the body shell, floor panel and bulkhead have not been considered as they were out of scope in this research. The value calculated therefore, solely relates to the torsional stiffness of the tubular chassis structure (See Figure 8).

<Insert Figure 8 about here>

Interestingly, the strain energy in the joint is constant irrespective of material selection. It does constrain the joining method hence, a combination of adhesive bonding and mechanical fastening is suitable for lightweight automotive space frame chassis (Mohamad *et al.,* 2017; Soo *et al.,* 2017).

CRASH SAFETY

Although the vehicle's crashworthiness is a major design consideration, occupant safety was not the primary objective for the originally designed Wikispeed Car (Socha *et al.,* 2013). As an established manufacturing group, the car has already complied with the minimum requirements of standardised crash testing - in this case the US-NCAP (Denning, 2012). To exceed this minimum test would require expensive and thorough testing (to a five-star rating) – i.e. *"$10,000 per crash plus the $14,500 material cost of the car, and $2,500 to deliver the car to the crash testing facility"* (Kupp *et al.*, 2015). Therefore, in order to achieve the five-star crash rating equivalency for the lightest possible chassis, only aluminium crashworthiness was experimentally conducted. In this section, four identical rockers used in the Wikispeed car have been evaluated (through theoretical calculations) for the load they can withstand before they yield in a crash (refer to Figure 9).

<Insert Figure 9 about here>

In the first stage of calculations, it can be seen that the force required to buckle the side rocker beam differs greatly with respect to material. From the second stage of calculations, it can be seen that the crush efficiency is independent of material type (refer to Table 4).

<Insert Table 4 about here>

The results imply that the current beam design made from magnesium would perform worst during a crash as the force required to buckle the beam is the lowest (between 95.2 kN and 134 kN). Steel has the largest bandwidth of force required for buckling and also requires the largest force for buckling (between 317 kN and 540 kN). Aluminium sits between the two with a compressive force between 234 kN and 293 kN required to buckle the beam. For a 35 mph frontal barrier test the crash efficiency of the side rocker beam is 98.2%. This means that at 35 mph, there would be no intrusion into the passenger compartment. This agrees with the findings of the Wikispeed crash test however, this calculation also implies a cabin deceleration of 28 m/s^2 takes place which if reduced, would also reduce the likelihood of injury. As none of the beams are expected to buckle in the said crash scenario (and therefore neither is there any intrusion into the passenger compartment), it could be argued that any of the three materials would be a valid choice for crashworthiness. However, to establish each materials' performance in more detail, further analytical calculations and numerical simulations at different speeds, alongside calculations and simulations of different crash conditions (such as a side barrier crash) should be carried out. Further investigation should be conducted on the frontal crash structure to evaluate the static and dynamic stiffness, and change in the structural response using the magnesium and steel material models available in LS-DYNA.

DISCUSSION OF THE WIKISPEED CAR

As the rockers have been made from a square tube with relatively thick walls - the consequence is that the b/t ratio is 33.9 meaning that the beam will fail in yielding and not buckling. The desired structural resonance frequency should be in the region of 22-25 Hz. Calculations have been made to determine the body stiffness to reach a structural resonance frequency of 25 Hz. For the side rocker beam, it can be seen that with its current material selection, the beam would buckle under a bending moment of 1560 Nm or more. This equates to a mass of approximately 780 kg being placed at the centre of the beam, which is more than the total mass of the vehicle and more than twice that of the rigidly fixed masses.

The bending moment imparted on the beam due to the rigidly fixed masses (as well as the passengers) is unlikely to exceed 964 Nm and as there are two side rocker beams sharing this load, thus resulting in a minimum safety factor of two. This material change for the two beams would also result in a weight saving of 8 kg, while costing approximately £12 less, based on the material mean cost per unit mass. Therefore, evaluating the results from the bending stiffness of the car chassis, it is highly recommended to change the material from aluminium to magnesium to correlate the theoretical results with the mechanical analysis. Magnesium will also save 3 kg weight per beam which is 12 kg on the whole chassis for the same material price per beam. The results also indicate that the bending stiffness is independent of material type and therefore, material selection will not impact upon this characteristic of the chassis' mechanical performance. One major issue is the choice of profile for the rockers. With the b/t ratio of 34, the rockers are going to fail by yielding and not by buckling.

As high fuel economy is a key design criterion for the vehicle, the degree to which torsional performance compromise can be made in favour of reducing weight, should be the main consideration. To this end, magnesium or aluminium both represent viable alternatives – the decision depends upon whether a weight saving of 36% justifies having a beam with half the torsional performance (that is 3.29° for aluminium vs 6.67° for magnesium?). Accounting for the parts left out in the assumptions would most likely account for this deficiency but should be further investigated in order to make a valid assertion. From the third and final set of body in torsion calculations, it can be seen that magnesium has the highest joint efficiency (77.1%), steel has the smallest (41.8%) and aluminium sits between the two with (68.4%). The strain energy in the rocker beam is ten times that of the B-pillar due to their respective lengths, thus there would be a larger improvement of vehicle torsional performance by improving the torsional performance of the side rocker beam. Rocker beams made of magnesium show the greatest strain energy, namely: 5.62×10^{-7}. As strain energy is equal to change in length divided by original length, it is expected that magnesium would show the largest deformation. This is reflected in the initial calculations, showing magnesium to have the greatest angle of rotation. Clearly this is not favourable, especially for a vehicle which already has a potentially relatively low torsional stiffness. To compensate for the material's (and potentially vehicle's) torsional deficiency, design work could be undertaken to add extra beams in the form of braces or a lattice structure to improve torsional stiffness, while still reducing the overall mass of the vehicle.

Fibre reinforced composite structures, such as the Wikispeed body shell, have exhibited energy absorption greater than similar metal structures (Lu *et al.*, 2018). Hence, it is necessary that for a full understanding of the vehicle's crashworthiness, this structure should be included in future crash analysis. The forces F_{max} and F_{avg} calculated in the second stage of calculations relate to the entire vehicle. In order to find the load in each of the side rocker beams the load must be partitioned. Figure 9 reveals that there are two main beams running along the length of each side of the vehicle (the lower being the side rocker beam) and each are identical in both size and shape. CF_{avg} is the average force per each of these beams, showing a force of 133 kN exerted on the aluminium beam, 129 kN on the steel beam and 70.4 kN on the magnesium beam. Comparing these values to those required to buckle the beams (by dividing the lowest force needed for buckling by the maximum force in the beam during the crash), reveals a worst-case safety factor of around 1.76 for aluminium, 2.46 for steel and 1.35 for magnesium, thus implying steel is also the most suitable material for the crashworthiness of the vehicle. When evaluating the crush efficiency, the eligible crush distance was taken as from the front bumper to the fire-wall or where the rockers begin. The analysis showed a crush efficiency of 98.16%, which means that for the car to be able to stop within the eligible crush distance it cannot do it without exceeding a maximum deceleration of 28 m/s^2. With a maximum force of 193 kN (calculated with max deceleration of 28 m/s^2) the rockers have a large margin before they would yield.

The primary factors that affect the fuel economy are regular travelling, weather, vehicle age and most importantly, traffic related factors. It can be estimated that if the Wikispeed Car (or any ICE engine vehicle) travels on the newly developed eco-system roads using advanced navigation systems, that there would be a saving of between 8.73% to 42.15% depending upon travel conditions i.e., traffic on the road (Zhou *et al.*, 2016). The water pump and the air-conditioner of the passenger vehicle are mostly affected due to the ambient temperature, whilst wind effects can also contribute in reducing the fuel economy by approximately up to 1% (U.S. Department of Energy, 2018). The engine is the most important factor that affects the fuel economy calculation due to engine loading, vehicle speed and the driver's aggressiveness, where the Wikispeed Car would have fuel economy of 5-20% on the flat roads superior to the car been driven on the hilly roads (Ciuffo and Fontaras, 2017). Another potential factor to increase the fuel economy of the Wikispeed Car, can be obtained by using optimal traffic light to vehicle communication system which would improve the fuel economy by almost 25% through the interaction between the driver and the traffic lights (Nasir *et al.,* 2014). Hence, although vehicle light-weighting can have a significant impact upon fuel economy, other external factors must also be considered as perhaps optimisation type problems. Optimisation of travel could be used via a coalescence of disruptive technologies that are dominating contemporary car manufacturing processes, for example, Industry 4.0 (Wand *et al.,* 2015) to build cars with advanced wireless monitoring and management systems. These technologies are already being adopted to varying extents to remove human error and increase vehicle performance (Lee *et al.*, 2015) – this trend is most likely set to continue.

CONCLUSION

Due to tougher EU legislations being introduced on reducing CO_2 emissions, automotive manufacturers are increasingly applying lightweight as a technological solution to obtain desirable environmental impact improvements. Vehicle mass reduction can be obtained through downsizing but also through substitution of the traditional automotive materials by lightweight materials, such as magnesium. Although aluminium alloy application has gained prominence, magnesium proves to be a promising contender to meet future demands of passenger vehicles. The research findings presented suggest that for the Wikispeed Car, magnesium is the right material choice. With the key design criteria of the Wikispeed being high fuel economy, the potential benefits highlighted in this paper from substituting aluminium alloy 6061-T651 for magnesium EN-MB10020 are noteworthy. The ability to improve the fuel economy by 10% and reduce the production cost at the same time is useful information for any automotive designer - especially those in the open-source crowd-funded domain. Nevertheless, with the b/t ratio of 34, the rockers are going to fail by yielding and not by buckling. As mentioned the crush length of frontal impact structure is 27% short. The way the crash beams have been orientated they are not going to buckle or yield - they are simply going to collapse. However, the cross bar needs to be orientated in this way to distribute the load between both sides, and the thickness of the beams might give it the needed rigidity to act as a good crash structure. It is therefore advisable for engineering designers to consider changing the material of the chassis to magnesium EN-MB10020 while implementing braces; although this will add more material to the vehicle it will be compensated for in the large reduction in vehicle mass of 110 kg. In addition to this research presented, a wider and more holistic view of passenger vehicle usage is required, beyond the design of the car itself. Such work should involve an integrated coalescence of disruptive innovative technologies such as global positioning systems, computational intelligence, internet of things and sensor based technologies (perhaps under the guise of Industry 4.0) to optimise passenger travel.

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Figure 1 - Weight Reduction Potential for High Strength Steel

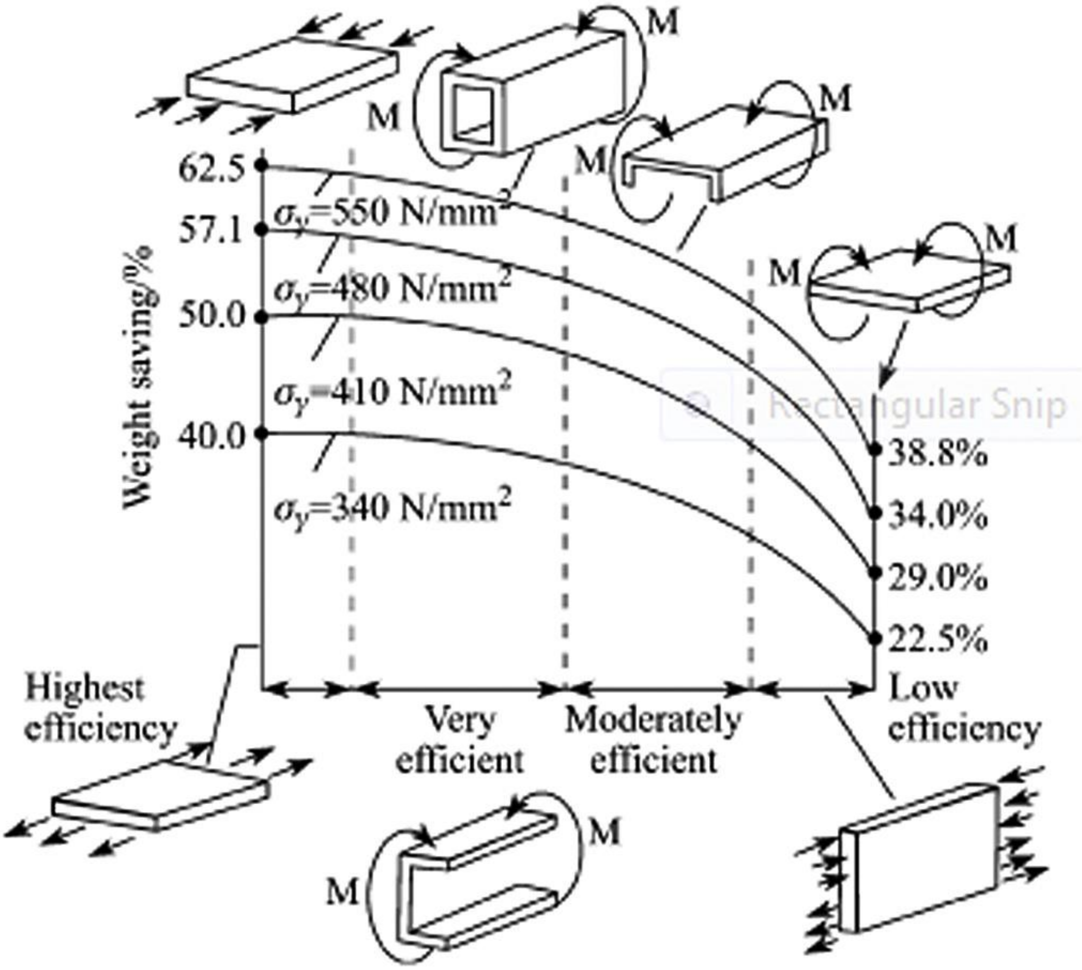

Figure 2 - The Flow Chart of the Methodology Used in this Paper

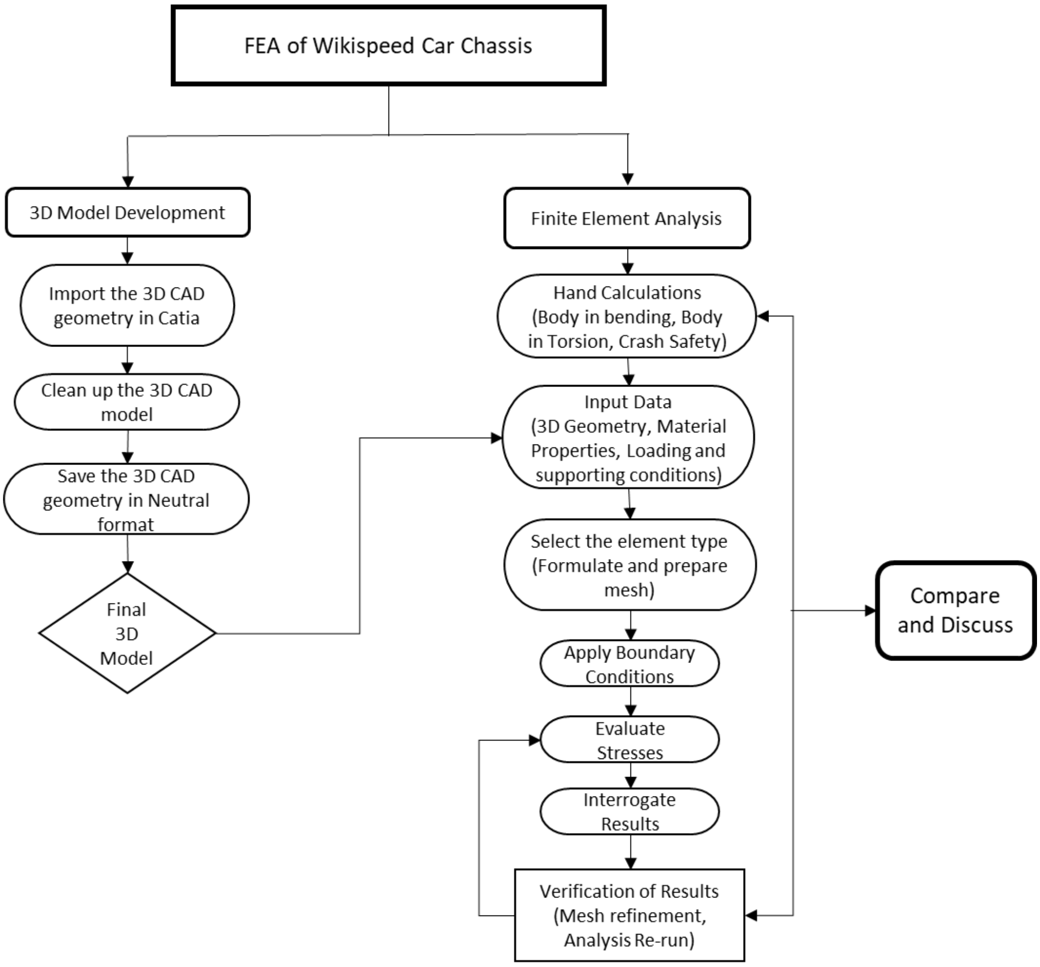

Table 1 - Material Properties

Name	UTS (MPa)	Yield Strength (MPa)	Shear Modulus (GPa)	Young's Modulus (Pa)	Poisson's Ratio	Density (kg/m^3)	Cost (£/kg)
BS EN 10025-3:2004 Structural Steel S275N	350 – 510	205 - 275	77.5 - 83.5	2.00E+11 - 2.21E+11	0.29 - 0.32	7800 – 7900	0.407 - 0.414
Aluminium Alloy 6061 - T651	276 – 305	241 - 266	26 - 27.3	6.80E+10 - 7.15E+10	0.33 - 0.343	2700 - 2730	1.57 - 1.8
Magnesium EN-MB10020	175 – 235	65 - 100	16 - 18	4.40E+10 - 4.55E+10	0.28 - 0.295	1730 - 1750	1.72 - 1.79

Figure 3 - FE Analysis on One of the Rocker Beams Made from Steel

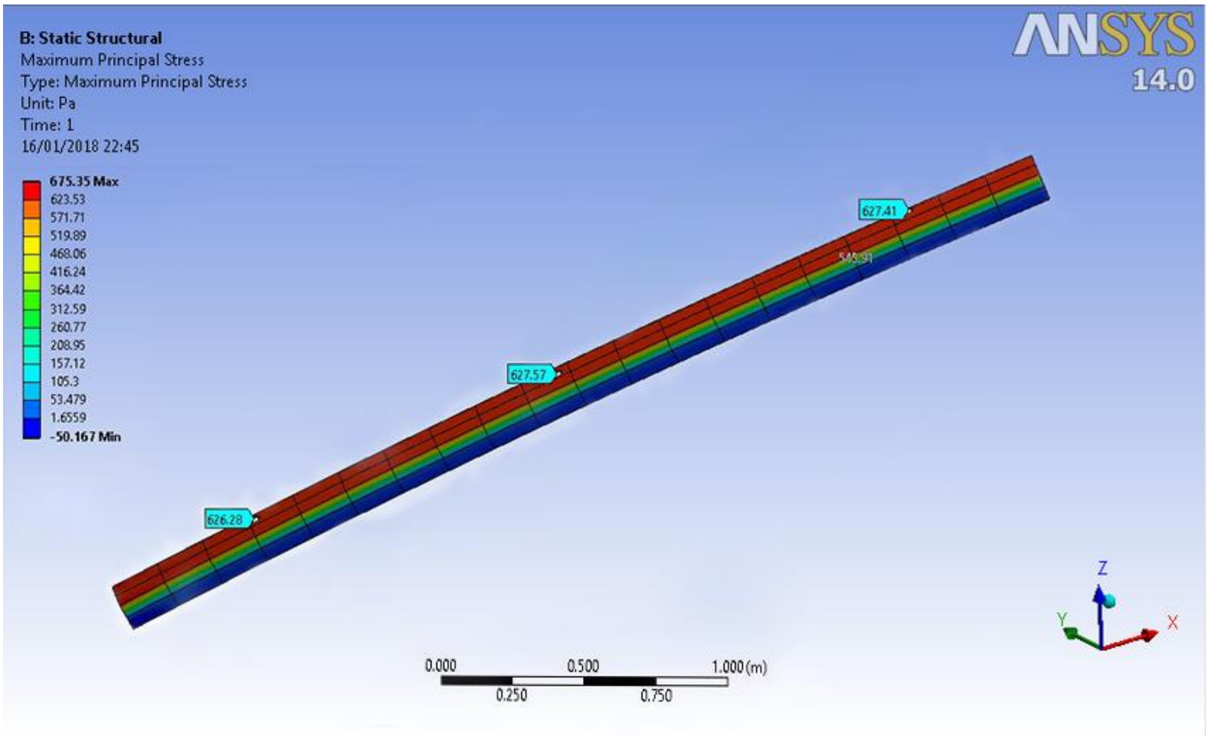

Figure 4 - Forces Acting on the Rocker Beam

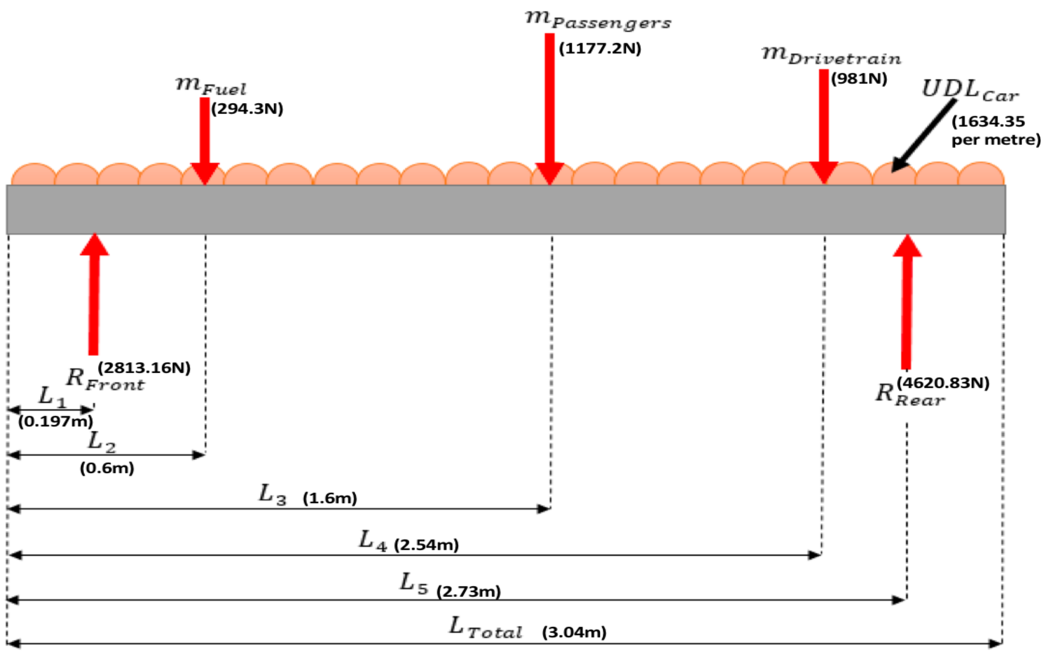

Table 2 - Results of Rocker Bending Analysis

Material	Steel	Aluminium	Magnesium
σ_{CR}	626.4 MPa	218.9 MPa	136.9 MPa
M_{CR}	23.66 kNm	8.27 kNm	5.17 kNm
Weight	31.6 kg	10.92 kg	7 kg
Price	£13.08	£19.66	£19.55

Figure 5 - Rocker Under Bending with Material as Magnesium

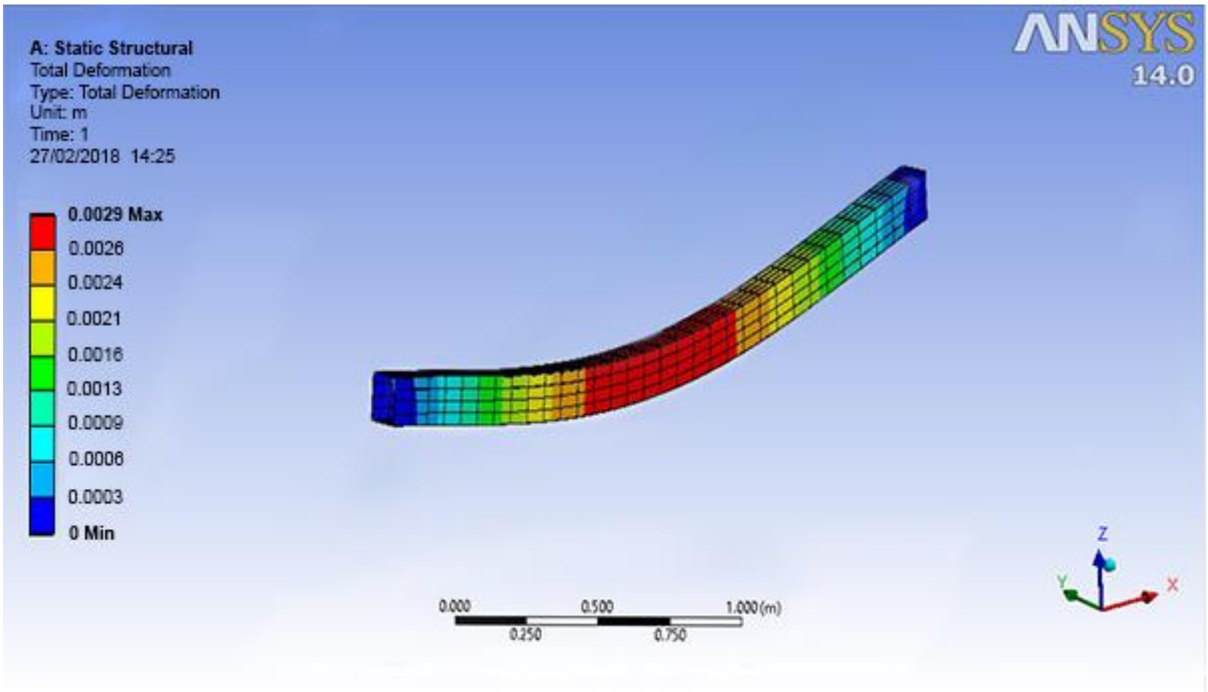

Figure 6 - Rocker Safety Factor with Material as Magnesium

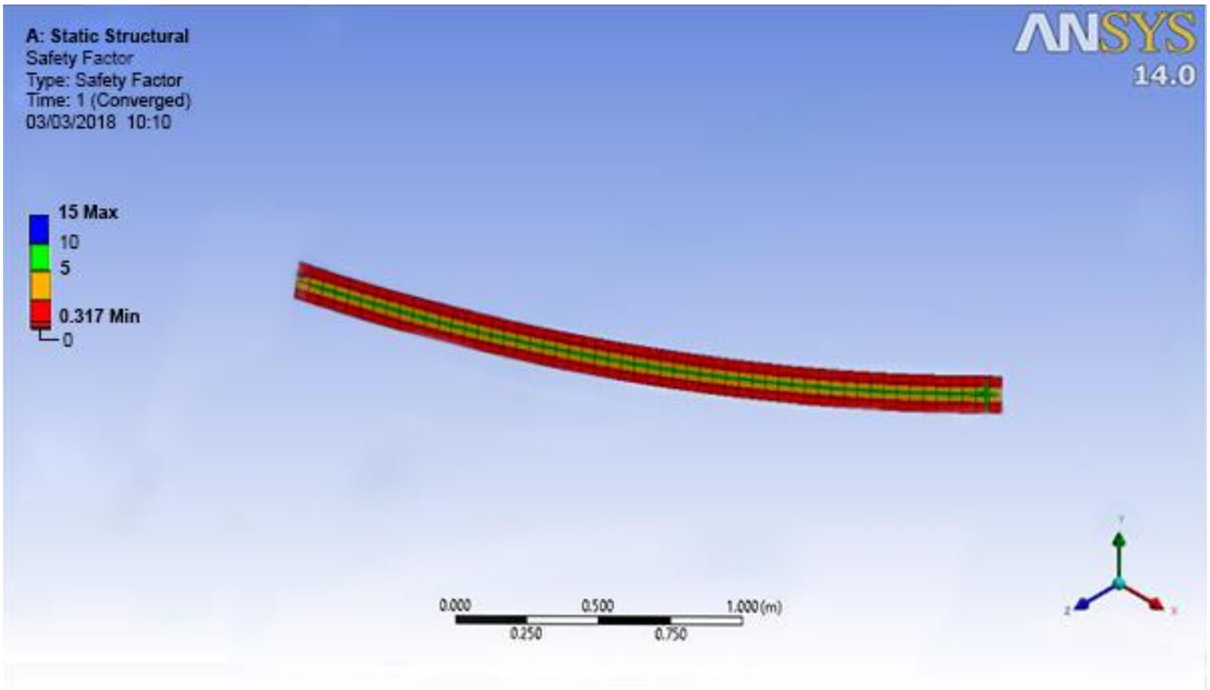

Table 3 - Torsional Calculation Results

Material	Steel	Aluminium	Magnesium
θ_{Rocker}	2.99deg	8.91deg	14.48deg
e_{Rocker}	3.77e-6 M^2	1.11e-5 M^2	1.11e-5 M^2
$e_{Hinge\ pillar}$	3.77e-6 M^2	1.71e-6 M^2	1.71e-6 M^2
F	41.8%	68.93%	77.42%
e_{BEAM}^{a}	$3.60x10^{-6}$	1.19 $x10^{-6}$	5.62 $x10^{-6}$
e_{BEAM}^{b}	$3.60x10^{-7}$	1.19 $x10^{-7}$	5.62 10^{-7}
e_{JOINT}	2.5 $x10^{-6}$	-	-
Σ		70.43 MPa	
K		12879.8 Nm/deg	

Figure 7 - Total Deformation on the Side Frame

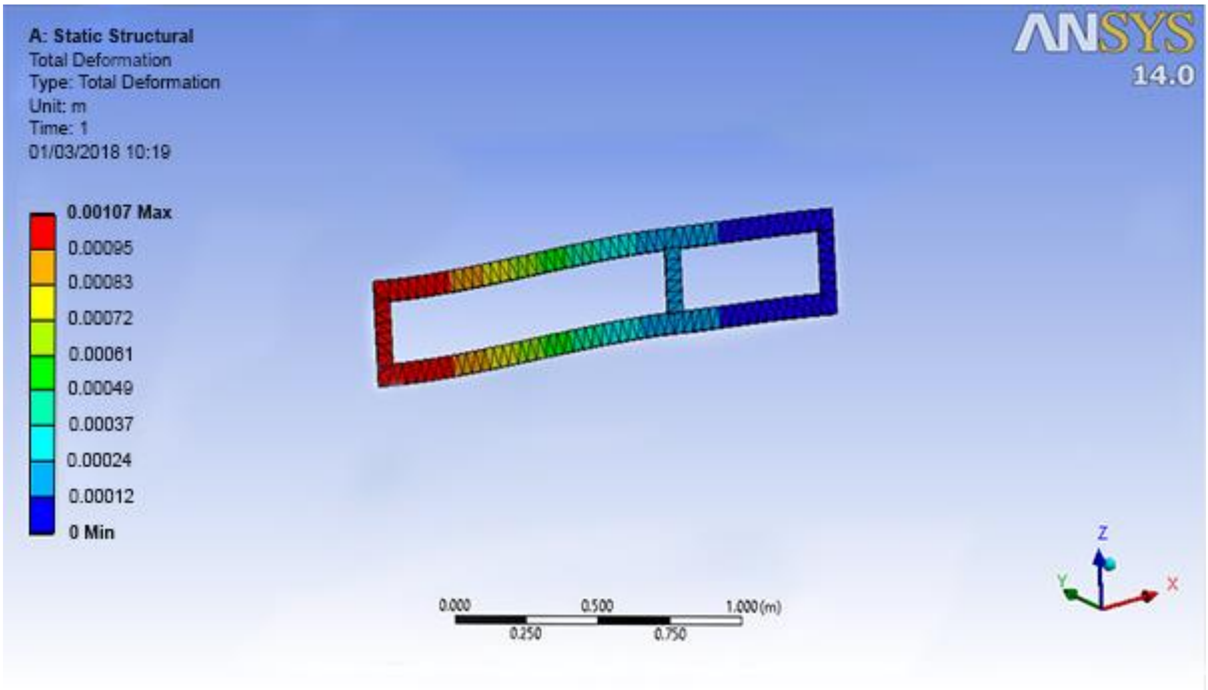

Figure 8 - Torsional Performance of Wikispeed Car Chassis

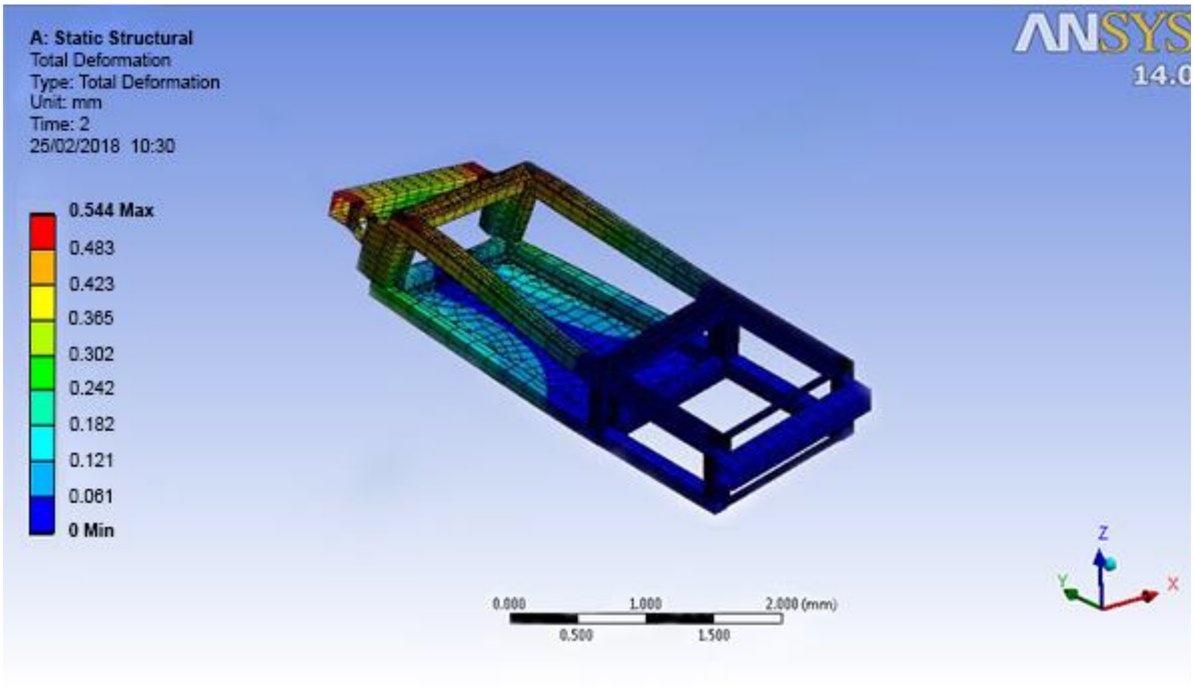

Figure 9 - Chassis of the Wikispeed Car with Yellow Highlighted Rockers

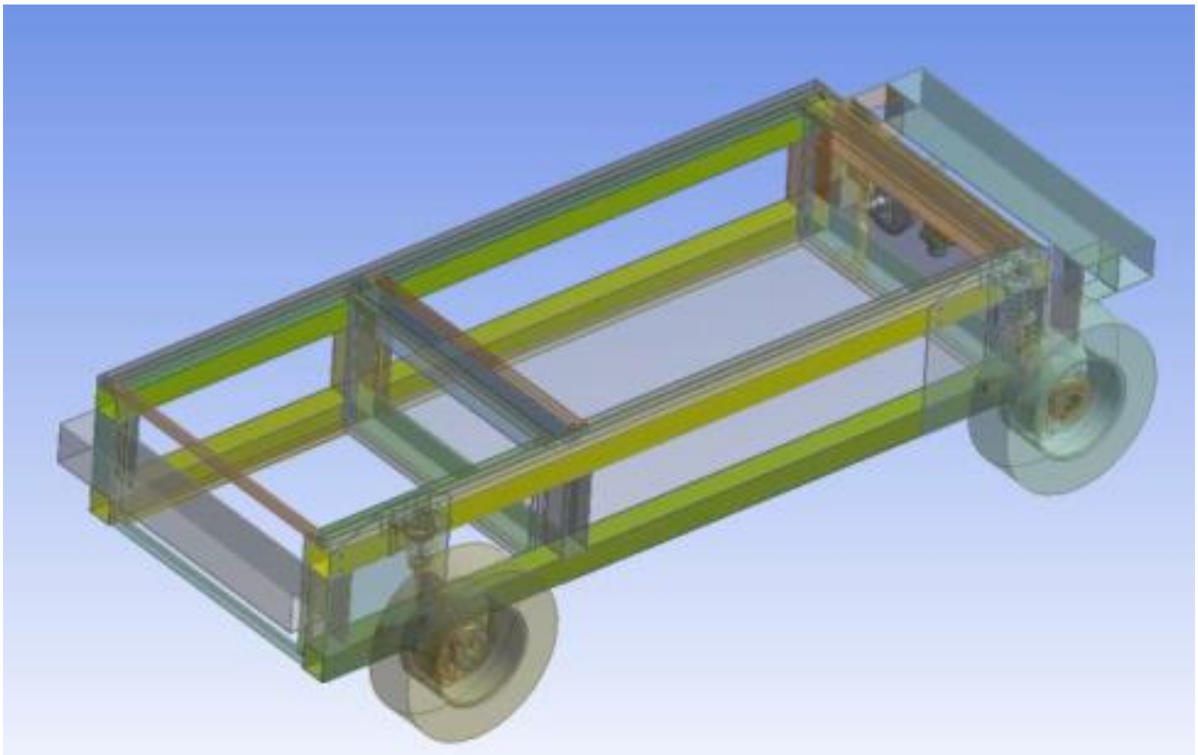

Table 4 - Crashworthiness Calculation Results

Calculations	**Aluminium**	**Steel**	**Magnesium**
w_1 (mm)	96.4	188	135
w_2 (mm)	76.9	110	96.1
P_{U1} (kN)	293	540	134
P_{U2} (kN)	234	317	95.2
η (%)	98.16	-	-
F_{max} (kN)	193	350	163
F_{avg} (kN)	189	343	160
CF_{avg} (kN)	133	129	70.4